

AD A 053449

AD No. \_\_\_\_\_  
DDC FILE COPY

12 He

NRL Report 8180

# Hydrophone Preamplifier Optimization

## Prediction of Hydrophone Self-Noise by a Noise Model

A. C. TIMS

*Transducer Branch  
Underwater Sound Reference Division  
Orlando, Florida*

March 17, 1978

DDC  
RECEIVED  
MAY 2 1978  
F



NAVAL RESEARCH LABORATORY  
Washington, D.C.

Approved for public release; distribution unlimited.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1 REPORT NUMBER <b>24</b> <b>NRL 8180</b>	2 GOVT ACCESSION NO.	3 RECIPIENT'S CATALOG NUMBER
4 TITLE (and Subtitle) <b>HYDROPHONE PREAMPLIFIER OPTIMIZATION</b> Prediction of Hydrophone Self-Noise by a Noise Model		5 TYPE OF REPORT & PERIOD COVERED Interim report on a continuing NRL Problem
7 AUTHOR(s) <b>24</b> <b>Allan C. Tims</b>		6 PERFORMING ORG REPORT NUMBER
9 PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Underwater Sound Reference Division P.O. Box 8337, Orlando, FL 32856		8 CONTRACT OR GRANT NUMBER(s)
11 CONTROLLING OFFICE NAME AND ADDRESS Department of the Navy Office of Naval Research Arlington, VA 22217		10 PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS PE: 62711N Project/Task: ZF11-121-003 Problem: 82S02-31.701
14 MONITORING AGENCY NAME & ADDRESS, if different from Controlling Office		12 REPORT DATE March 17, 1978
		13 NUMBER OF PAGES <b>22</b>
		15 SECURITY CLASS. (of this report) <b>UNCLASSIFIED</b> 15a DECLASSIFICATION/DOWNGRADING SCHEDULE
16 DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited. <b>7</b> Interim report <b>15</b> 17-072		
17 DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) <b>26</b> <b>61121</b> <b>17</b> <b>ZF11121043</b>		
18 SUPPLEMENTARY NOTES		
19 KEY WORDS (Continue on reverse side if necessary and identify by block number) Hydrophone preamplifier Electrical noise Preamplifier Self-noise		
20 ABSTRACT (Continue on reverse side if necessary and identify by block number) This report presents analysis of the self-noise which determines the threshold pressure level in hydrophone designs. The noise present in the acoustic sensor, coupling network, and preamplifier input stage are represented by an equivalent circuit noise model. A model provides an effective method to predict in advance of sensor-preamplifier construction the noise levels expected for a specific design.		

**DDC**  
**RECEIVED**  
**MAY 2 1978**  
**F**

DD FORM 1 JAN 73 1473

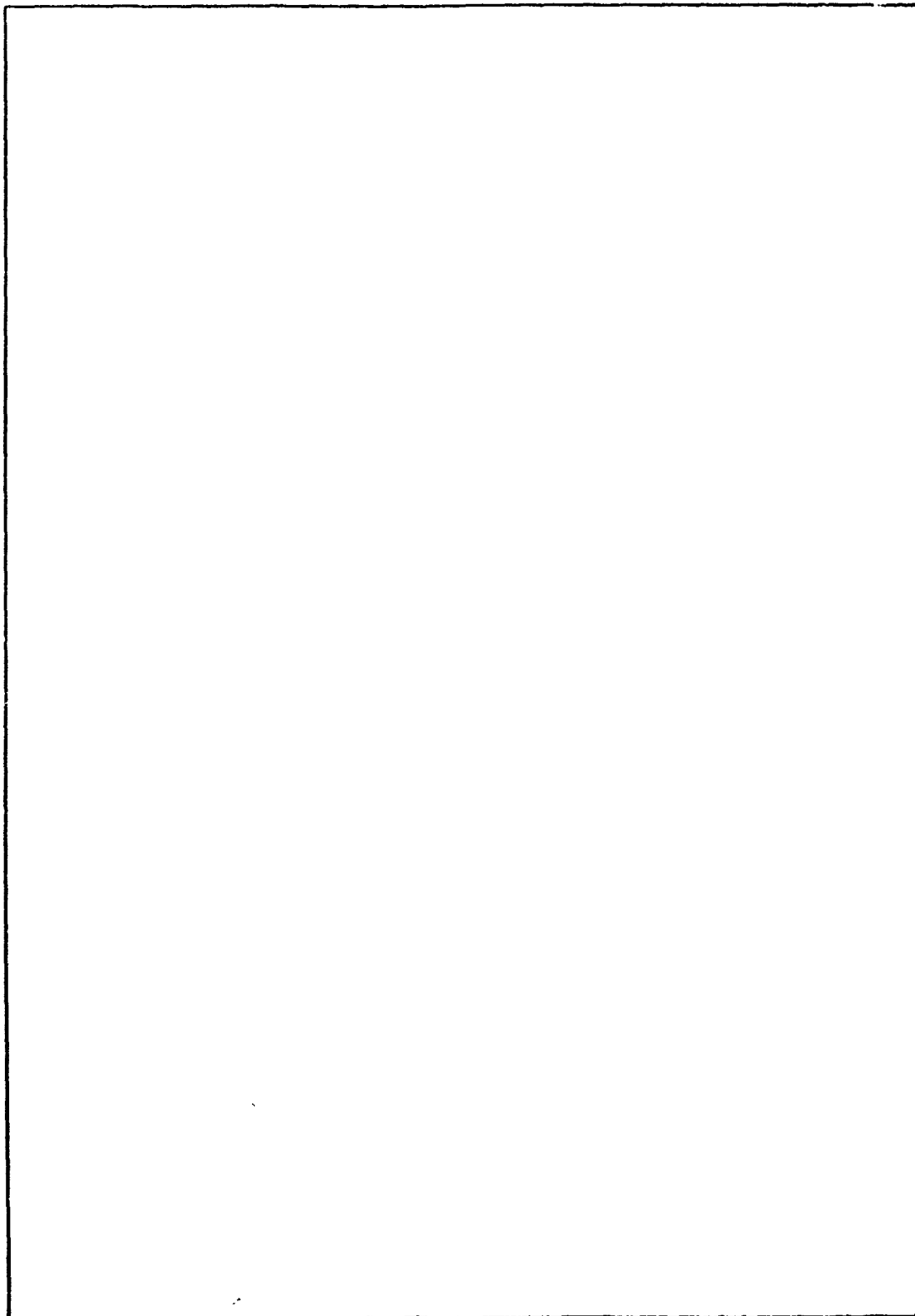
EDITION OF 1 NOV 65 IS OBSOLETE  
S/N 0102-LF-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

251 150

hpf

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)



## CONTENTS

INTRODUCTION .....	1
THERMAL NOISE .....	1
NOISE-CIRCUIT ANALYSIS CONSIDERATIONS .....	2
THE NOISE MODEL .....	2
CONCLUSION .....	7
ACKNOWLEDGMENTS .....	7
REFERENCES .....	7
BIBLIOGRAPHY .....	7
APPENDIX A—The Effects of Circuit Values on Self-Noise .....	8
APPENDIX B—JFETs for Low-Noise Circuit Applications .....	17
APPENDIX C—Low-Noise Hydrophone Preamplifier .....	19

ACCESSION for	
NTIS	White Section <input checked="" type="checkbox"/>
DDC	Buff Section <input type="checkbox"/>
UNANNOUNCED	<input type="checkbox"/>
JUSTIFICATION	
ACCESSION/AVAILABILITY CODES	
SPECIAL	
A	

## HYDROPHONE PREAMPLIFIER OPTIMIZATION PREDICTION OF HYDROPHONE SELF-NOISE BY A NOISE MODEL

### INTRODUCTION

A hydrophone consists of two well-defined components — the acoustic sensor element and the preamplifier. For noise-measuring hydrophones the design focal points are high acoustic sensitivity for the sensor element and low self-noise from the preamplifier [1]. When the requirements of omnidirectionality and broad bandwidth are added to these, the sensor element can become so small that inadequate impedance loading is provided for the preamplifier, resulting in prohibitive self-noise.

Self-noise is a result of the preamplifier electronic-noise mechanisms and the thermal-noise contribution of the sensor element. Most of the noise originates at the input stage of the preamplifier; the acoustic element actively contributes thermal noise proportional to its impedance loading on the input.

This report presents noise modeling and circuit analysis of the noise which limits the threshold pressure level in any hydrophone design. Using noise analysis, a designer can establish minimum noise levels and understand the limiting factors for a specific design, without actual construction and after-the-fact noise measurements [2].

### THERMAL NOISE

According to the well-known Johnson-Nyquist equation, electrons in every conductor are in random motion. This motion is temperature dependent, and the mean-square thermal-noise voltage is

$$E_v^2 = 4kTR\Delta f,$$

where

$k$  = Boltzmann's constant,  $1.38 \times 10^{-23}$  J/K,

$T$  = temperature of the conductor in K,

$R$  = resistance, or real part of the conductor's impedance,

and

$\Delta f$  = noise bandwidth in Hz.

Figure 1 shows an equivalent circuit for thermal noise, represented by a noise-voltage generator in series with a noiseless resistance. According to Norton's theorem, the series circuit of Fig. 1 can be replaced by a constant-current generator in parallel with a resistance as in Fig. 2.

Manuscript submitted November 1, 1977.

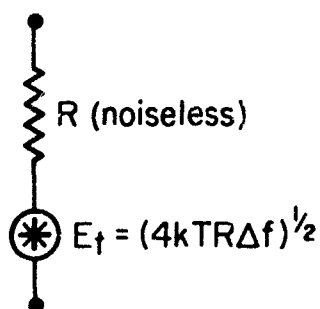


Fig. 1 - Equivalent circuit for thermal-noise-voltage generator

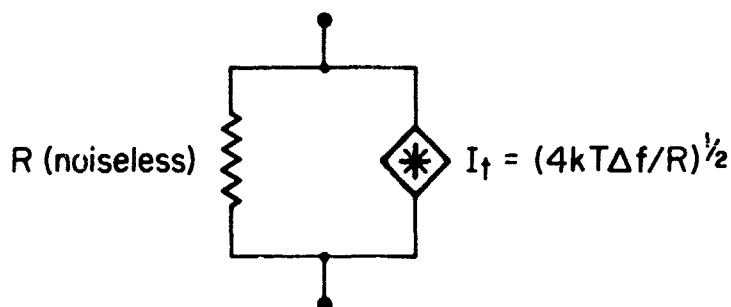


Fig. 2 - Equivalent circuit for thermal-noise-current generator

## NOISE-CIRCUIT ANALYSIS CONSIDERATIONS

When several noise sources are acting simultaneously in a linear network, the total noise is the sum of the sources acting independently, with the other voltage sources short-circuited and the other current sources open-circuited. The contributions from each source are added, so that the magnitude of the noise is increased by the contribution from each source.

Equivalent-noise generators represent a large number of component frequencies with a random distribution of amplitudes and phases. When there is no relationship between instantaneous values from independent generators, their voltages are uncorrelated. However, if their voltages are equal and fully correlated, the maximum error caused by the assumption of independence is only 3 dB. If the voltages are partially correlated, or if one is of much greater amplitude than the other, the error is less. Thus one can assume the correlation to be zero, with little error.

## THE NOISE MODEL

To perform a noise analysis of a hydrophone system, one represents the components of the hydrophone sensor and preamplifier by a noise model. Since the input noise is determined by the sensor impedance and by the first transistor stage of the preamplifier, modeling is confined to this area. To further simplify analysis, one assumes the sensor to be small in comparison with the wavelength, the mechanical losses very small, and the impedance almost entirely reactive.

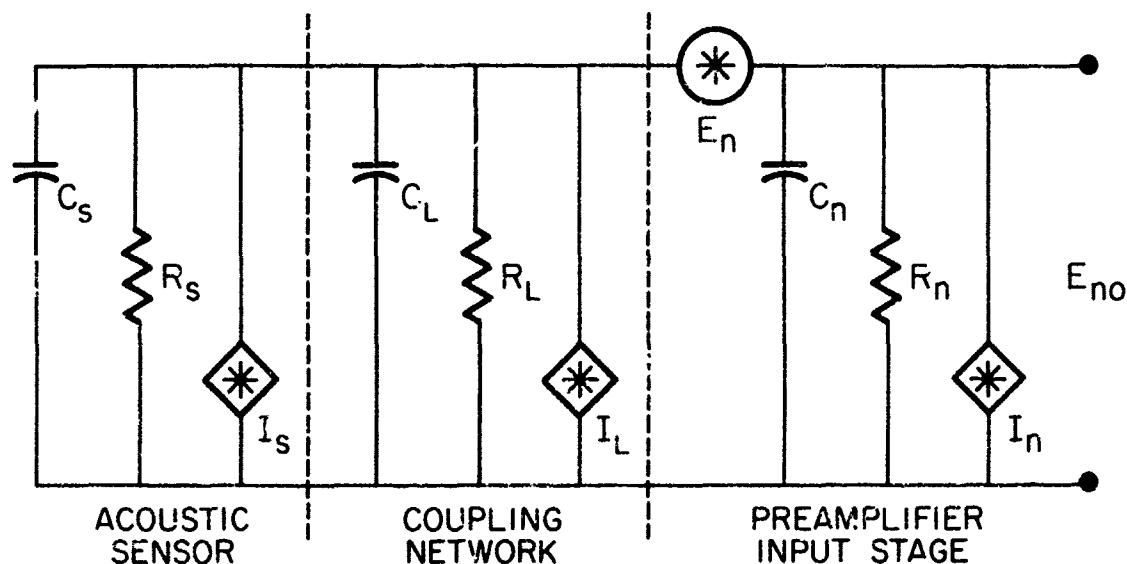


Fig. 3 - Noise model of hydrophone

The schematic diagram of Fig. 3 shows the  $E_n - I_n$  equivalent-noise representation for a hydrophone electronic system, with its three distinctive sections: the acoustic sensor element, the coupling network, and the preamplifier input stage. In Fig. 3,

$C_s$  = capacitance of the acoustic sensor element,

$C_L$  = shunt capacitance across  $C_s$  due to inner electrode capacitance and dielectric changes caused by the acoustic coupling medium of the hydrophone sensor head,

$C_n$  = preamplifier input capacitance,

$R_s$  = resistance of the sensor,

$R_L$  = resistance across  $R_s$  caused by the volume resistance of the acoustic coupling medium ( $R_L = R_H R_s / (R_s - R_H)$ , where  $R_H$  is the measured terminal resistance of the oil-filled hydrophone head),

$R_n$  = preamplifier input resistance,

$E_n$  = input-transistor midband noise voltage,

$I_n$  = input-transistor midband noise current,

$I_s$  = sensor rms equivalent-noise-current generator,

and

$I_L$  = coupling network rms equivalent-noise current.

To find the equivalent input noise  $E_{ni}$ , the total output noise  $E_{no}$  is calculated using Kirchhoff's laws. The equivalent input noise is the output noise  $E_{no}$  divided by the system

gain  $K$ , where the system gain can be either a voltage, current, or impedance transfer function as needed.

In Fig. 3 the mean-square output noise voltage is

$$E_{no}^2 = E_n^2 + (\text{Re}Z_T)^2 I_T^2. \quad (1)$$

where

$$(\text{Re}Z_T)^2 = R_T^2 / (1 + \omega^2 R_T^2 C_T^2) \quad (2)$$

is the square of the real part of the impedance, with

$$R_T = 1 / (1/R_s + 1/R_L + 1/R_n) \quad (3)$$

and

$$C_T = C_s + C_L + C_n. \quad (4)$$

Also, in (1),

$$I_T^2 = I_s^2 + I_L^2 + I_n^2, \quad (5)$$

where

$$I_s^2 = 4kT/R_s \quad (6)$$

and

$$I_L^2 = 4kT/R_L. \quad (7)$$

This leads to

$$E_{no}^2 = E_n^2 + I_T^2 [R_T^2 / (1 + \omega^2 R_T^2 C_T^2)]. \quad (8)$$

$E_{no}^2$  is the total noise at the output of the system, in  $V^2/\text{Hz}$ , with the amplifier gain unity. If the amplifier gain is greater than unity, the total noise is simply the product of the unity  $E_{no}^2$  term and the gain  $A$ , since amplification does not change the signal-to-noise ratio.

To compute the voltage transfer function  $K$ , consider the circuit of Fig. 4, a simplified circuit of Fig. 3, where  $C_s$  and  $R_T$  are as previously defined,  $C_D = C_T - C_s$ ,  $V_n$  and  $V_o$  are the input and output voltages of the network, and  $i_1$  and  $i_2$  the appropriate loop currents. Then

$$\begin{bmatrix} (R_T + 1/j\omega C_s) & -R_T \\ -R_T & (R_T + 1/j\omega C_D) \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} V_n \\ 0 \end{bmatrix}, \quad (9)$$

$$i_2 = V_n R_T / \Delta, \quad (10)$$

and

$$V_o = i_2 (Z_o) = i_2 / j\omega C_D. \quad (11)$$

Thus

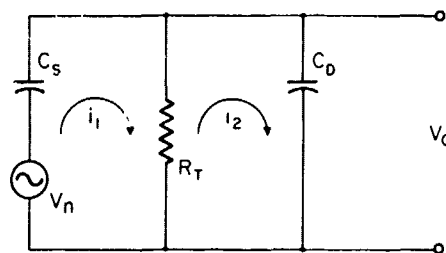
$$V_o / V_n = \frac{R_T / j\omega C_D}{(R_T + 1/j\omega C_s)(R_T + 1/j\omega C_D) - R_T^2} = K \quad (12)$$

and

$$K = \frac{R_T}{R_T[(C_s + C_D)/C_s] - j/\omega C_s}. \quad (13)$$



Fig. 4 - Simplified circuit of Fig. 3 with input voltage source  $V_n$  and output voltage  $V_o$



Since  $C_T \approx C_D + C_s$ , then

$$K = \omega C_s R_T / (\omega C_T R_T - j); \quad (14)$$

the modulus of (14) squared becomes  $K^2$ , where

$$K^2 = \omega^2 C_s^2 R_T^2 / (\omega^2 C_T^2 R_T^2 + 1). \quad (15)$$

The mean-square equivalent input noise is

$$E_{ni}^2 = E_{no}^2 / K^2. \quad (16)$$

Thus

$$E_{ni}^2 = E_{no}^2 \{ (1 + \omega^2 C_T^2 R_T^2) / \omega^2 R_T^2 C_s^2 \} + (I_s^2 + I_L^2 + I_n^2) / \omega^2 C_s^2. \quad (17)$$

In the circuit analysis,  $E_n$  and  $I_n$  are given as midband values. In order for the noise voltage and current to be representative of device-noise characteristics, a shaping factor is applied for each case, as a function of frequency. For noise voltage, the factor is

$$E_n^2(f) = E_n^2 [(1 + F_1/f) + (f/F_2)^2], \quad (18)$$

and for the noise current,

$$I_n^2(f) = I_n^2 [(1 + F_3/f) + (f/F_4)^2], \quad (19)$$

where  $F_1$  and  $F_2$  are low- and high-frequency  $E_n$  noise corners,  $F_3$  and  $F_4$  are low- and high-frequency  $I_n$  noise corners, and  $f$  is the frequency of interest [2, p.142].

A Bode plot of (18) and (19) is shown in Fig. 5. At frequencies below  $F_1$  and  $F_3$  the noise rises 3 dB/octave to characterize the  $1/f$  noise mechanisms of the input transistor; at midband the noise is independent of frequency; and at  $F_2$  and  $F_4$  the noise rises 6 dB/octave, because of transistor gain rolloff.

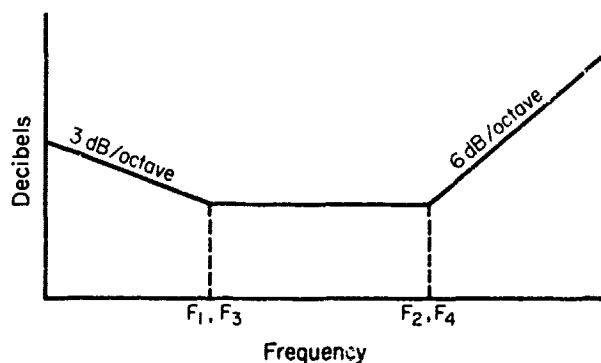


Fig. 5 - Shaping factor, noise characteristics

A program was written for the Hewlett-Packard 9810A calculator which solves (8), (15), (17), (18), and (19). Values for resistance, capacitance, noise current, noise voltage, and frequency can be readily substituted to quickly determine their effect on the output noise, the input noise, or the transfer function. (Appendix A describes the effects of varying the values of components.)

Figure 6 shows the equivalent noise pressure curve for a USRD type H56 standard-reference hydrophone, which was calculated from the measured noise voltage. Also shown is the theoretical equivalent noise pressure, derived as outlined in this report. Knudsen's sea-state-zero curve is indicated as a reference.

The equivalent noise pressure is computed by using  $E_{no}$  and free-field voltage sensitivity  $M_e$  of the hydrophone. If  $M_e$  represents the hydrophone sensitivity at the output of the preamplifier, then

$$P_{en} = E_{no} - M_e, \quad (20)$$

where the units are decibels referred to  $1 \mu\text{Pa}$ .

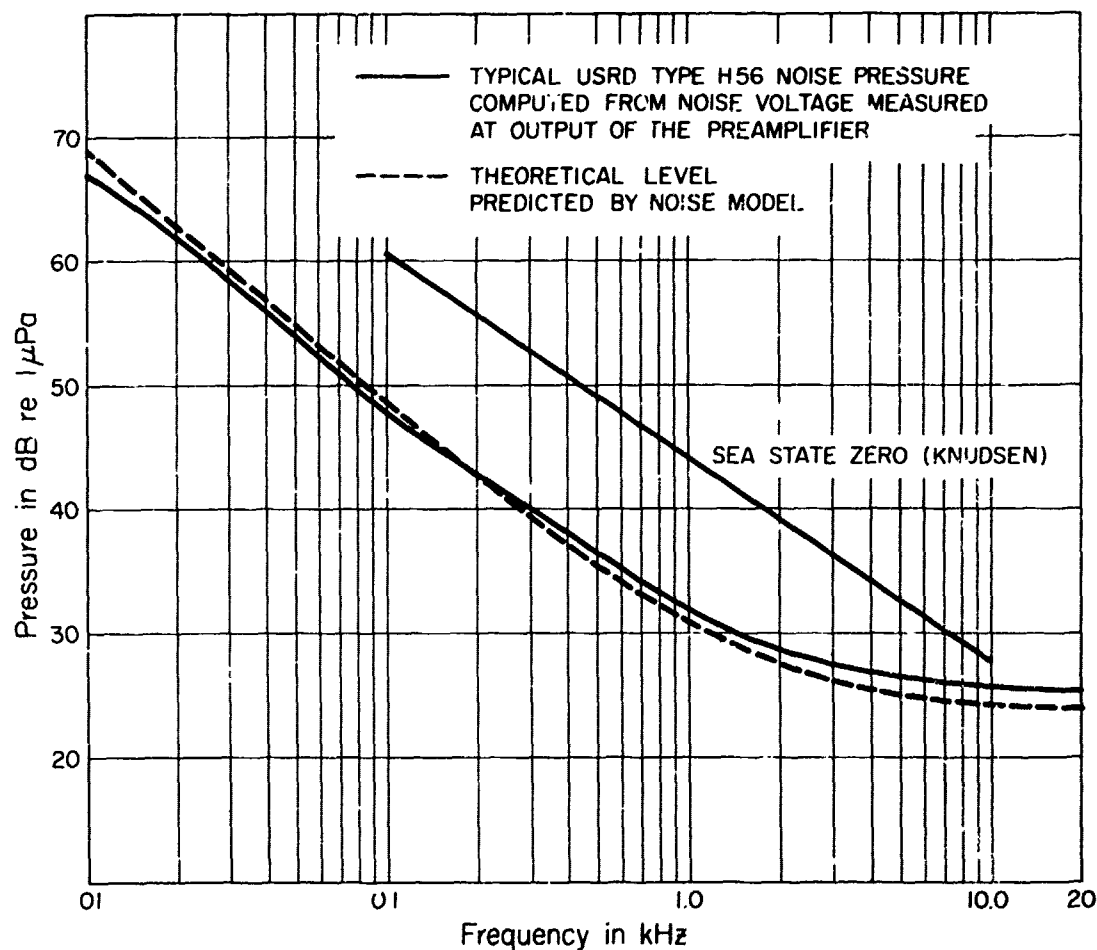


Fig. 6 - Equivalent noise pressure

## CONCLUSION

Often a black-art approach is used to design a low-noise hydrophone. However, noise modeling provides an effective method to predict in advance of actual circuit or sensor construction the self-noise level to be expected from a specific design. With the aid of a mini-computer or a good programmable calculator, analysis can be quick and accurate. In most cases, the noise model need not be more complex than presented herein.

## ACKNOWLEDGMENTS

The author thanks Theodore A. Henriquez and Craig K. Brown of the USRD and Dr. Hans Fuehrer of Rollins College, Winter Park, Florida, for their impetus, expert guidance, and review. Portions of this report have been submitted to the School of Continuing Studies, Rollins College, for the Bachelor of Science degree.

## REFERENCES

1. R.W. Timme, R.L. Davidson, and A.C. Tims, "Expendable Hydrophone for Sonobuoy Application," NRL Report 7644, 17 Sept. 1973.
2. C.D. Motchenbacher and F.C. Fitchen, *Low-Noise Electronic Design*, John Wiley, New York, 1973.

## BIBLIOGRAPHY (Electronic Noise and Low-Noise Hydrophone Design)

- I.D. Groves, Jr., "Low-Noise Hydrophone for All Underwater Ocean Environments," Eighth International Congress on Acoustics, London, July 1974, Vol. 2.
- I.D. Groves, Jr., "A Hydrophone for Measuring Acoustic Ambient Noise in the Ocean at Low Frequencies" (USRD Type H62), NRL Report 7738, 15 Apr. 1974.
- T.A. Henriquez, "An Extended-Range Hydrophone for Measuring Ocean Noise," *J. Acoust. Soc. Amer.* **52**, 1450-1455 (1972).
- W.A. Rheinfelder, *Design of Low-Noise Transistor Input Circuits*, Hayden, New York, 1964.
- B. Watson, "Audio-Frequency Noise Characteristics of Junction FETs," Application Note AN 74-4, Siliconix Incorporated, Santa Clara, Calif., Aug. 1974.
- A. Van der Ziel, *Noise*, Prentice-Hall, New York, 1954.

# **Appendix A** **THE EFFECTS OF CIRCUIT VALUES ON SELF-NOISE**

The following figures present the resulting noise levels when one component value of the noise model is varied while the others are held constant. Some curves are of equivalent input noise  $E_{ni}$ , and others are of equivalent output noise  $E_{no}$ ; tabulation of the transfer function  $K$  is also presented. The curves are a plot of dB versus frequency; therefore,

$$E_{ni} \text{ (dB)} = E_{no} \text{ (dB)} - K \text{ (dB)}. \quad (\text{A1})$$

For the noise model in Fig. A1, the constant values for the components are given in Table A1.

Table A1 - Constant Values for the Noise-Model Circuit of Fig. A1

$C_s$	$C_L$	$C_n$	$R_s$	$R_L$	$R_n$	$I_n$	$I_s$	$I_L$	$E_n$
100 pF	10 pF	20 pF	1 G $\Omega$	1 G $\Omega$	1 G $\Omega$	1 fA/ $\sqrt{\text{Hz}}$	$\sqrt{4KT/R_s}$ A/ $\sqrt{\text{Hz}}$	$\sqrt{4KT/R_L}$ A/ $\sqrt{\text{Hz}}$	1 nV/ $\sqrt{\text{Hz}}$

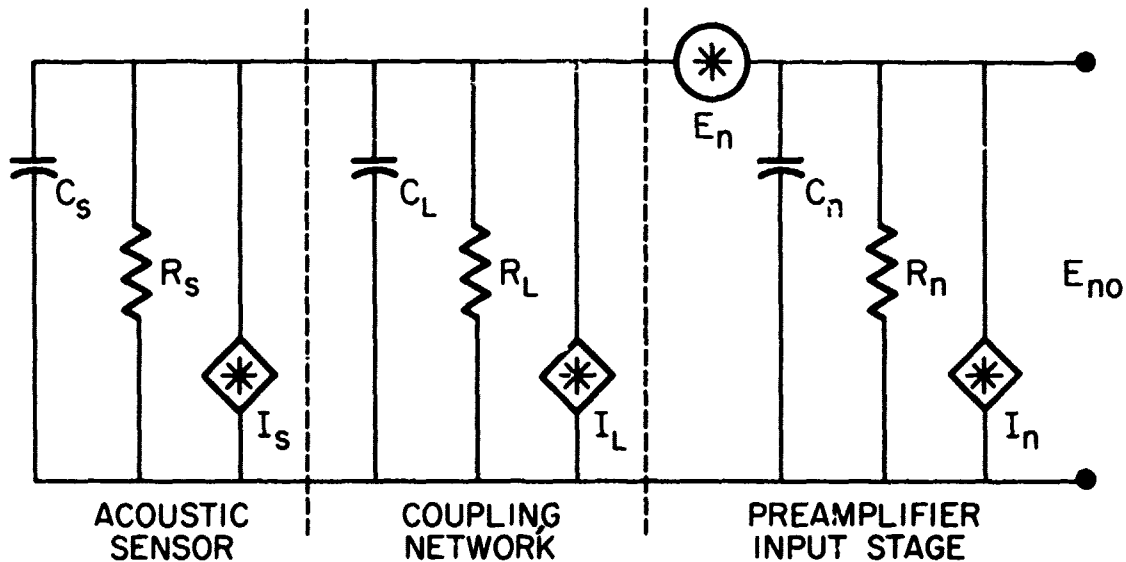


Fig. A1 - Noise model of hydrophone

Figure A2 shows  $E_{ni}$  for various sensor capacitances  $C_s$ , with all other circuit values constant as given in Table A1. The effect of impedance is exhibited where the input noise is decreased by 6 dB as the source capacitance is doubled. Note the  $K$  and the low-frequency rolloff associated with a high-impedance source. For example, with  $C_s = 20$  pF and  $f = 10$  Hz, the output noise will be down by -10.8 dB ( $K$  from Table A2), where

$$E_{no} \text{ (dB)} = E_{ni} \text{ (dB)} + K \text{ (dB)}. \quad (\text{A2})$$

Table A2 – Values of  $K$  as a Function of Sensor Capacitance  $C_s$  for Fig. A2

$C_s$ (pF)	$K$ (dB)			
	10 Hz	50 Hz	100 Hz	20 kHz
20	-10.8	-8.1	-8.0	-8.0
40	-6.5	-4.9	-4.9	-4.9
80	-3.5	-2.8	-2.8	-2.8
100	-2.8	-2.3	-2.3	-2.3
200	-1.4	-1.2	-1.2	-1.2
500	-0.5	-0.5	-0.5	-0.5
1000	-0.3	-0.3	-0.3	-0.3

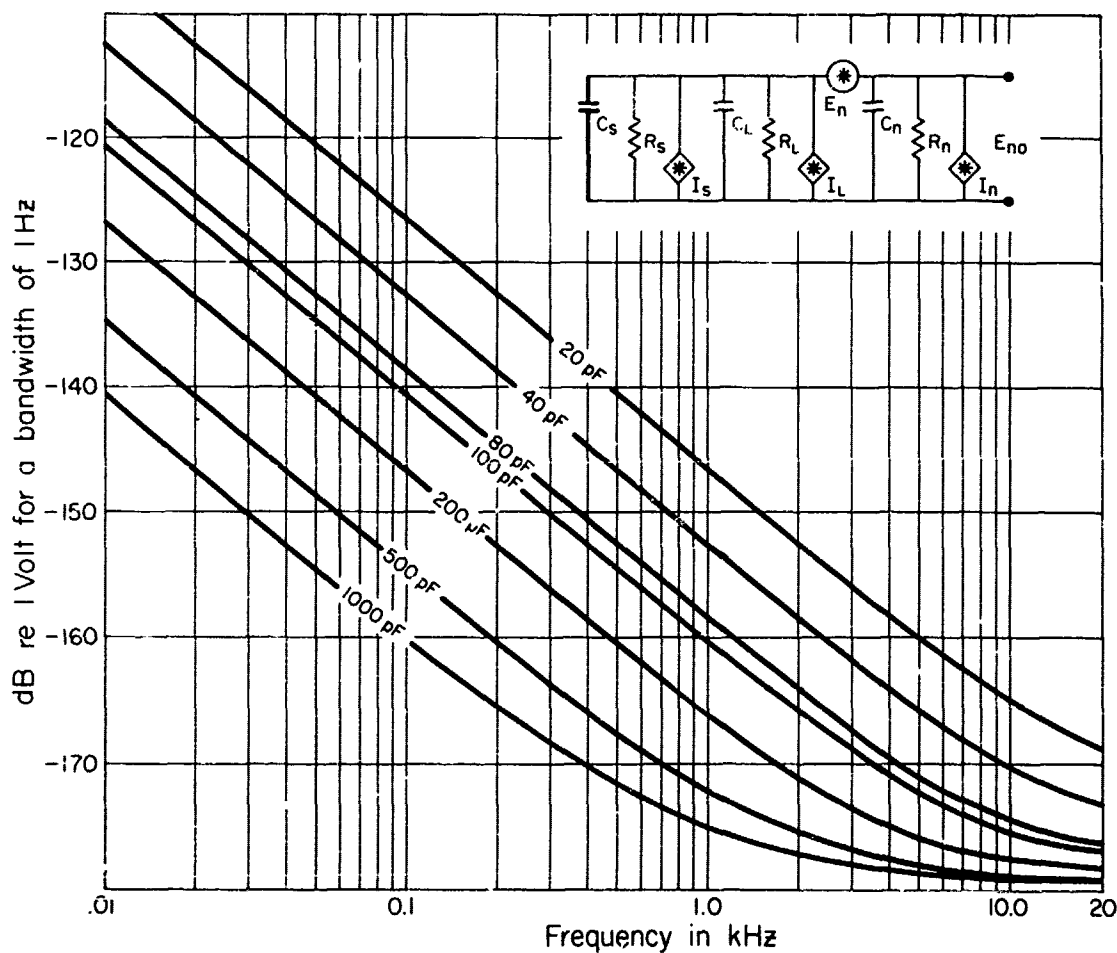


Fig. A2 – Equivalent noise input as a function of  $C_s$

Figure A3 presents  $E_{ni}$  as a function of shunt capacitance  $C_L$ , with other component values as given in Table A1.  $E_{ni}$  is not affected by  $C_L$  at low frequencies; however  $E_{no}$  is significantly influenced by the increase in  $K$ , as indicated by Eq. (A2) and Table A3. Note that

$$K(\text{dB}) \approx 20 \log [C_s' / (C_s + C_L + C_n)]. \quad (\text{A3})$$

Equation A3 is true where the values of  $K$  are constant with increasing frequency.

Table A3 gives the insertion loss  $K$  that occurs between a low-capacitance sensor element ( $C_s$ ) and the hydrophone preamplifier input impedance. Circuit designers are often unwittingly influenced by  $K$  when they design a preamplifier to have some specific gain, say 10 dB, with the input to the preamplifier short-circuited. This action usually loads the preamp by the input-coupling capacitor, which is usually several thousand picofarads. However, when the

Table A3 – Values of  $K$  as a Function of Shunt Capacitance  $C_L$  for Figure A3

$C_L$ (pF)	$K$ (dB)			
	10 Hz	50 Hz	100 Hz	20 k' ..
20	-3.4	-3.0	-2.9	-2.9
30	-3.9	-3.5	-3.5	-3.5
60	-5.4	-5.1	-5.1	-5.1
100	-7.1	-6.9	-6.9	-6.9
200	-10.2	-10.1	-10.0	-10.0

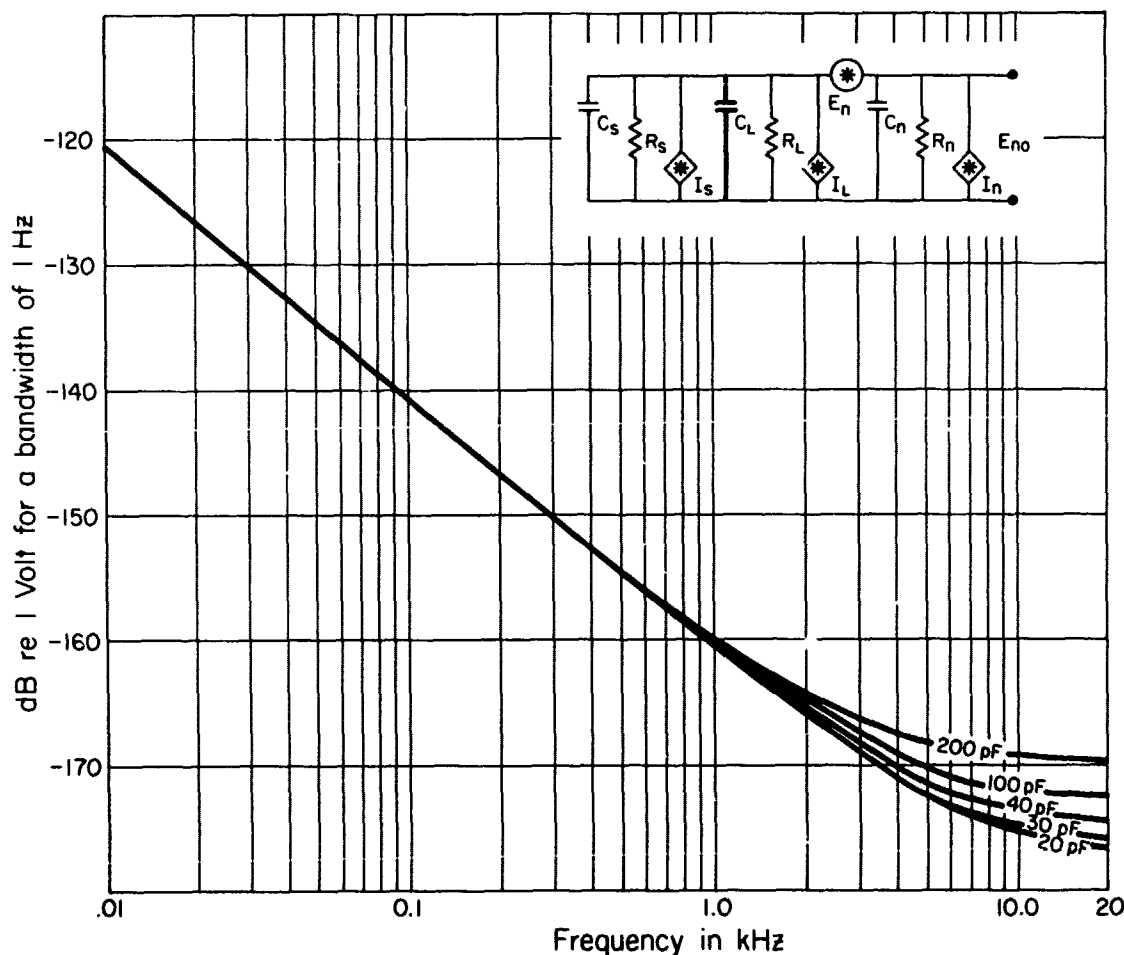


Fig. A3 – Equivalent noise input as a function of  $C_L$

preamplifier is used with a high-impedance source, the preamplifier gain drops to 7 or 8 dB, because the input coupling capacitor and the high-impedance sensor are in series and the preamplifier sees only the sensor. The insertion loss incurred is  $K$ .

Figure A4 displays the effect of input capacitance  $C_n$  on  $E_n$ , with all other circuit values as given in Table A1. The figure shows that the input capacitance has little effect on the equivalent input noise. However, for a very high impedance sensor,  $K$  should be carefully observed, because the input capacitance is added to  $C_L$ , and the sum in relation to  $C_s$  can cause  $K$  to become quite large.  $K$  can be approximated by

$$K(\text{dB}) \approx -20 \log [C_s / (C_s + C_L + C_n)]. \quad (\text{A4})$$

Values of  $K$  for Fig. A4 are given in Table A4.

Table A4 – Values of  $K$  as a Function of Input Capacitance  $C_n$  as Given in Fig. A4

$C_n$ (pF)	$K$ (dB)		
	10 Hz	50 Hz	20 kHz
5	-1.9	-1.2	-1.2
10	-2.2	-1.6	-1.6
15	-2.5	-1.9	-1.9
30	-3.4	-3.0	-3.0
40	-4.0	-3.5	-3.5

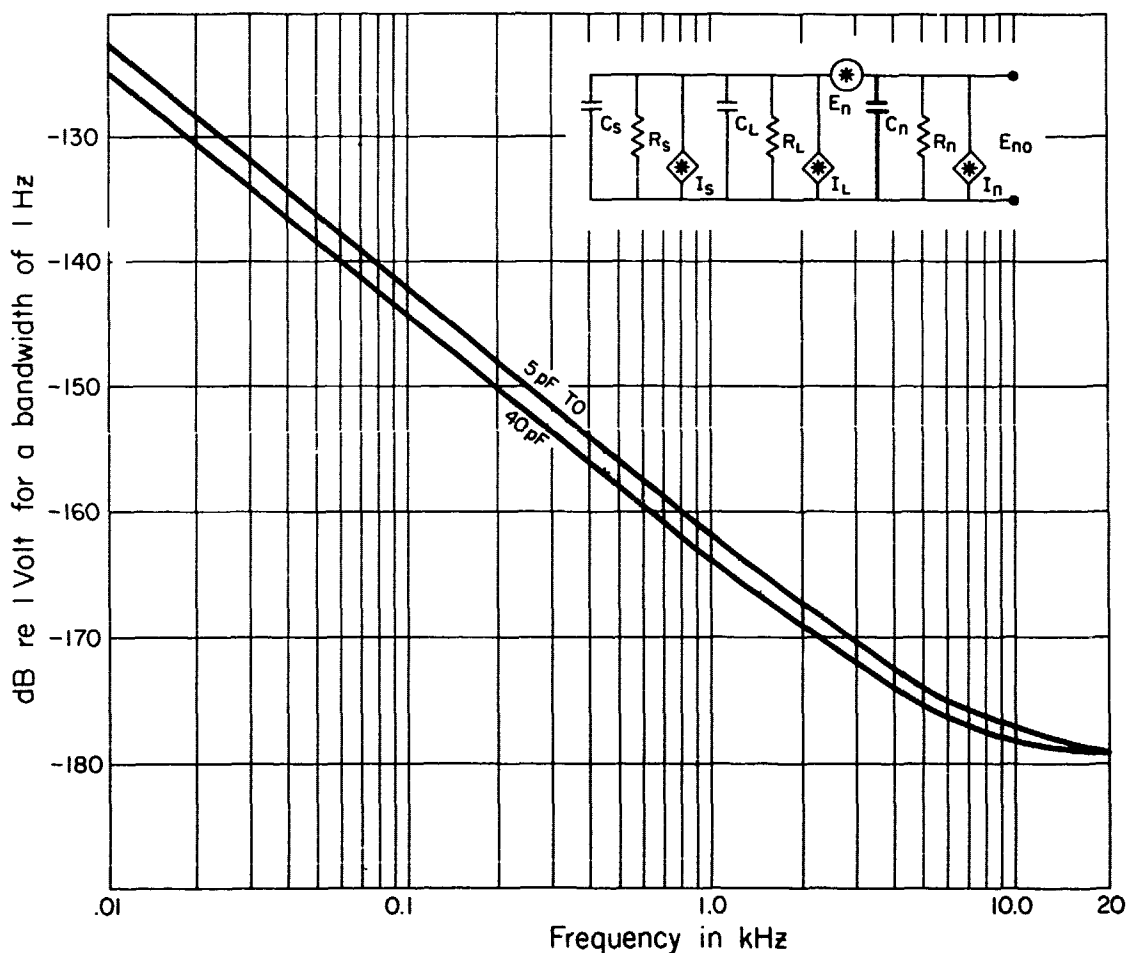


Fig. A4 – Equivalent noise input as a function of  $C_n$

Figure A5 shows  $E_{ni}$  as a function of sensor resistance  $R_s$ , with other circuit values as given in Table A1. With the constant values selected,  $E_{ni}$  is greatly influenced as  $R_s$  becomes less than  $10^9$  ohms. Consequently there are high values of  $K$  (Table A5) at low frequencies, where the value of  $K$  is determined by the  $RC$  combinations across the input of the preamplifier. The break frequency ( $-3$  dB down) is

$$f_{-3dB} = \frac{1}{2\pi R_T C_T}, \quad (A5)$$

where

$$R_T = \frac{1}{\frac{1}{R_s} + \frac{1}{R_L} + \frac{1}{R_n}} \quad (A6)$$

and

$$C_T = C_s + C_L + C_n. \quad (A7)$$

Table A5 – Values of  $K$  as a Function of Sensor Resistance  $R_s$  for the Curves Shown in Fig. A5

$R_s$ ( $\Omega$ )	$K$ (dB)					
	10 Hz	50 Hz	100 Hz	500 Hz	1 kHz	20 kHz
$10^7$	-24.2	-10.9	-6.4	-2.5	-2.4	-2.3
$10^8$	-7.3	-2.6	-2.4	-2.3	-2.3	-2.3
$10^9$	-2.8	-2.3	-2.3	-2.3	-2.3	-2.3
$10^{10}$	-2.6	-2.3	-2.3	-2.3	-2.3	-2.3
$10^{11}$	-2.5	-2.3	-2.3	-2.3	-2.3	-2.3

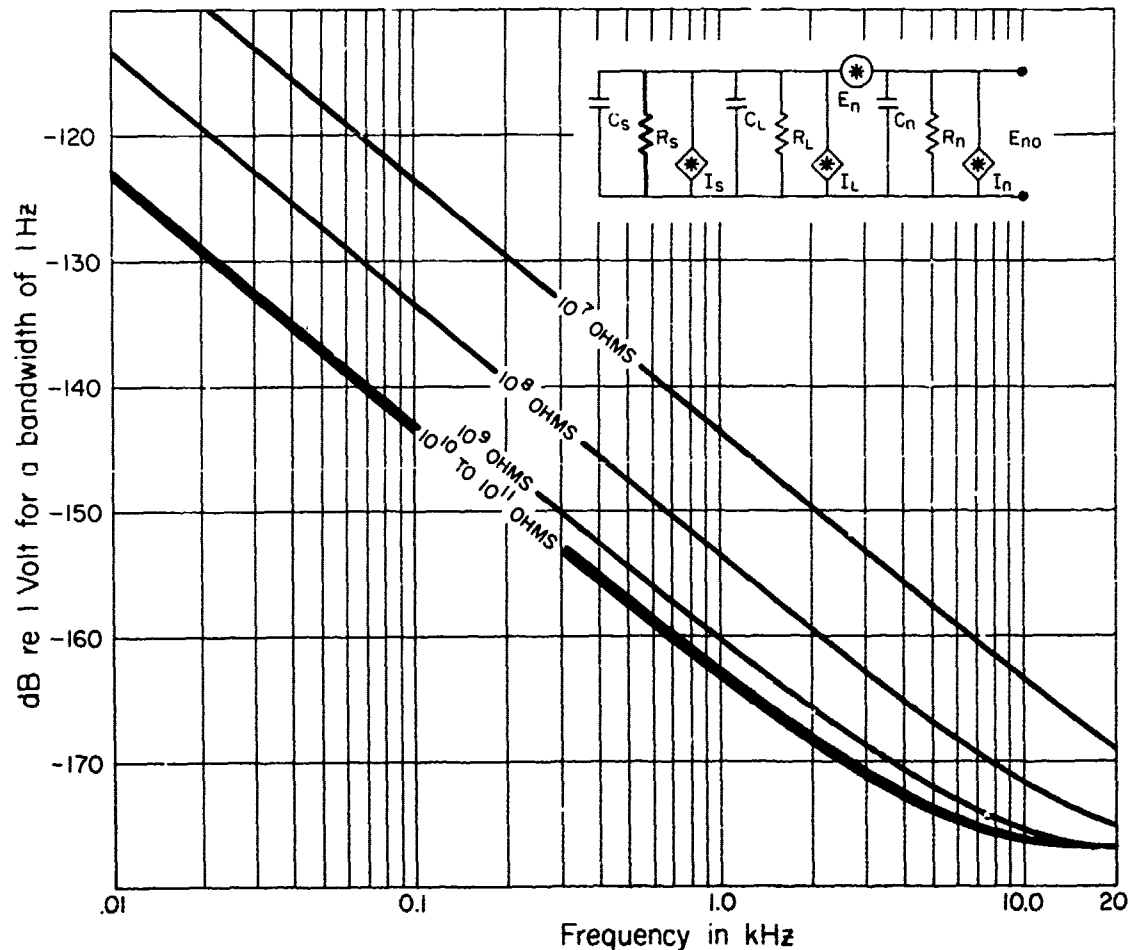


Fig. A5 – Equivalent noise input as a function of  $R_s$



In most hydrophone designs,  $R_s$  and  $R_L$  are one or two orders of magnitude greater than  $R_n$ ; also  $C_L$  and  $C_n$  are less than  $C_s$  such that

$$f_{3dB} \approx \frac{1}{2\pi R_n C_s}. \quad (A8)$$

The variation of  $E_{ni}$  and  $E_{no}$  with  $R_L$  is shown in Figs. A6 and A7 respectively. Low values of  $R_L$  can be very influential in the low-frequency response of a system with a high-impedance source. The total load across  $C_s$  is the parallel combination of  $R_s$  and  $R_L$  if the input impedance of the preamplifier is at least a factor of 10 greater. Under the given conditions, as the parallel combination of  $R_s$  and  $R_L$  becomes  $< 10^8$  ohms, the low-frequency rolloff of  $E_{no}$  becomes pronounced, as observed in Fig. A7. From Figs. A6 and A7,  $K$  values can be obtained where

$$K(\text{dB}) = E_{ni}(\text{dB}) - E_{no}(\text{dB}). \quad (A9)$$

The effects of varying  $R_n$ , with all other circuit values as given in Table A1, are plotted in Fig. A8. Values of  $E_{ni}$  and  $E_{no}$  are shown for  $R_n > 10^7$  ohms. As previously described for  $R_s$  and  $R_L$ ,  $R_n$  is most influential at low values and low frequencies, especially if its value is equal to or less than  $R_L$  or  $R_s$  or their parallel combination.

Noise voltage at the input of the preamplifier as a function of  $E_n$  is presented in Fig. A9. At this point of a hydrophone design, significant changes in self-noise can be made by careful selection of the input device (Appendixes B and C). For the best low-noise FETs the manufacturers give  $E_n$  at 10 Hz and 1 kHz in  $\text{nV}/\sqrt{\text{Hz}}$ . The noise in other devices is often disguised by giving broadband noise or a noise figure which relates to an amplifier with a specific input resistance.

$K$  is constant for all values of  $E_n$ ; it is determined by the values of the resistive and reactive components of the model.

Figure A10 gives  $E_{no}$  as a function of  $I_n$ . As with  $E_n$ ,  $I_n$  is input-device dependent, and the designer is given much latitude in device selections. The value of  $K$  is also constant, as with  $E_n$ .

A. C. TIMS

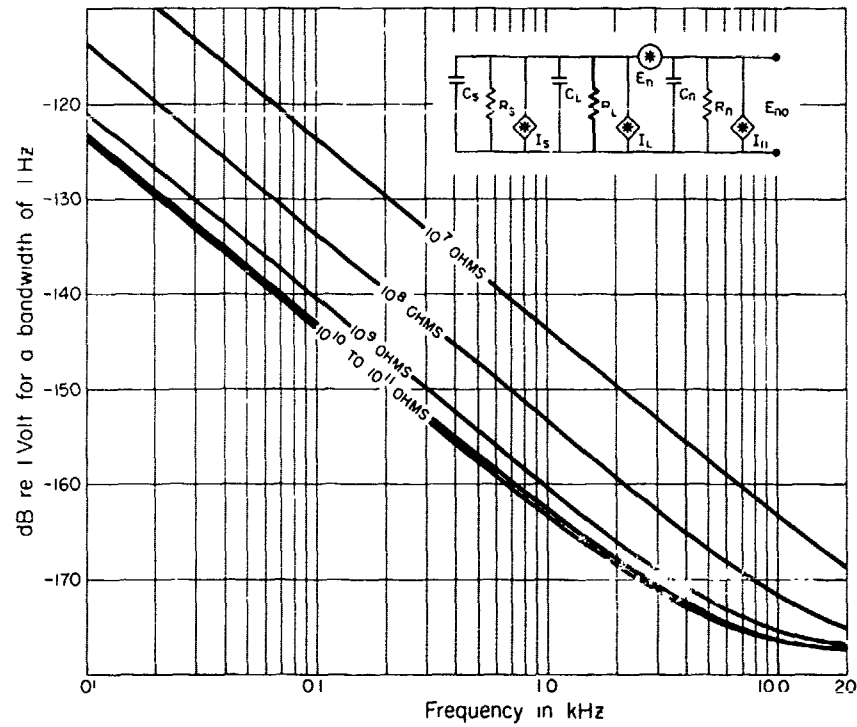


Fig. A6 - Equivalent noise input as a function of  $R_L$

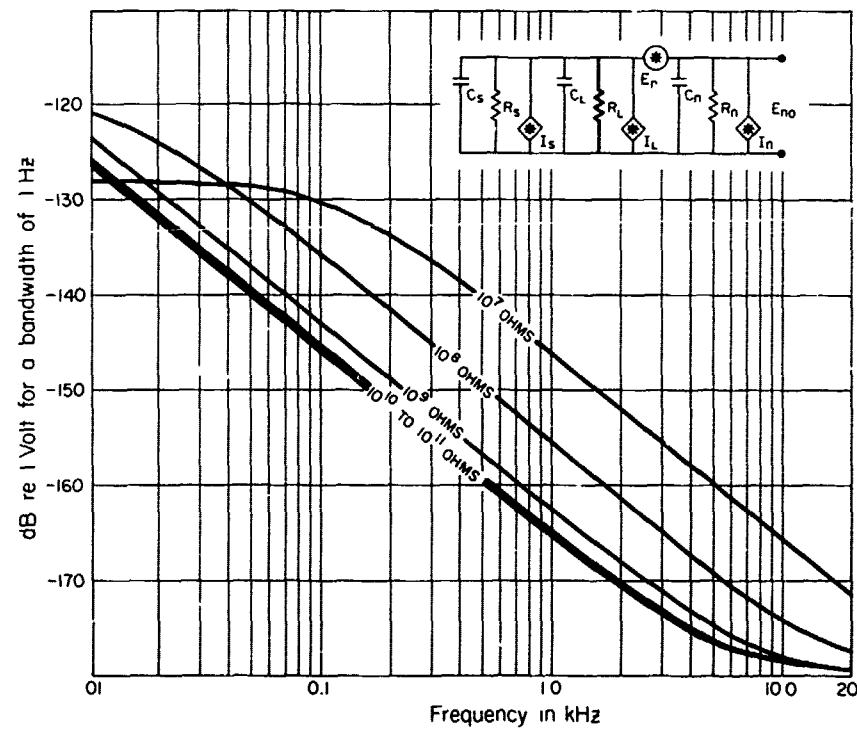


Fig. A7 - Equivalent noise output as a function of  $R_L$

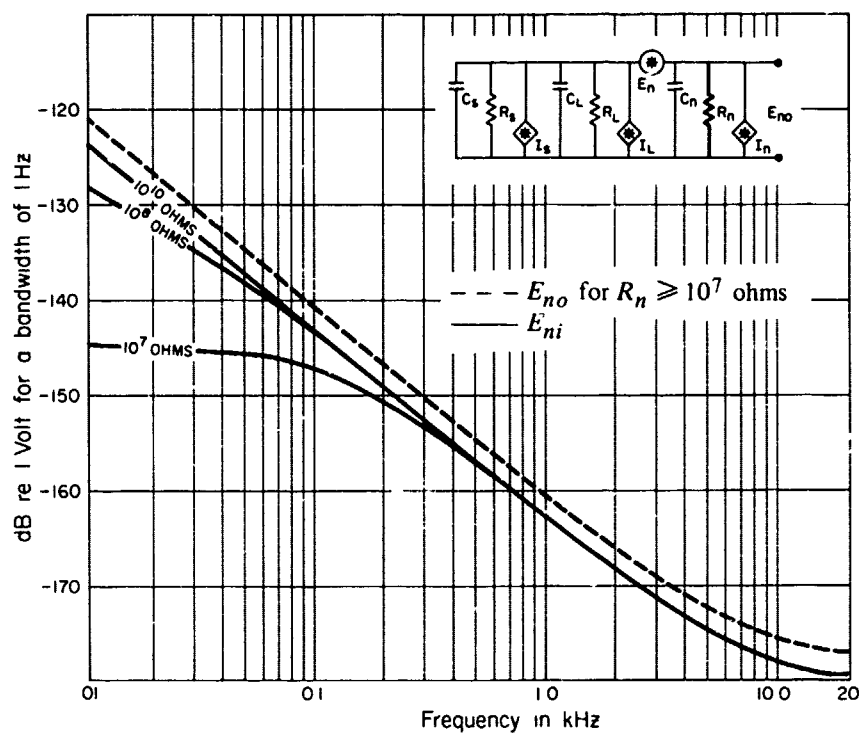


Fig. A8 - Equivalent noise as a function of  $R_n$

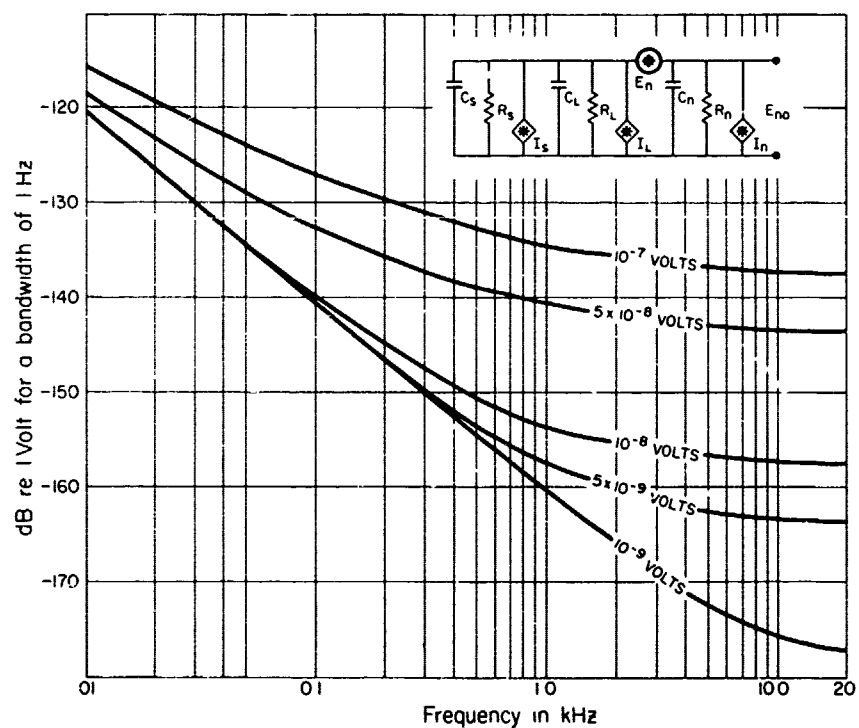


Fig. A9 - Equivalent noise input as a function of  $E_n$

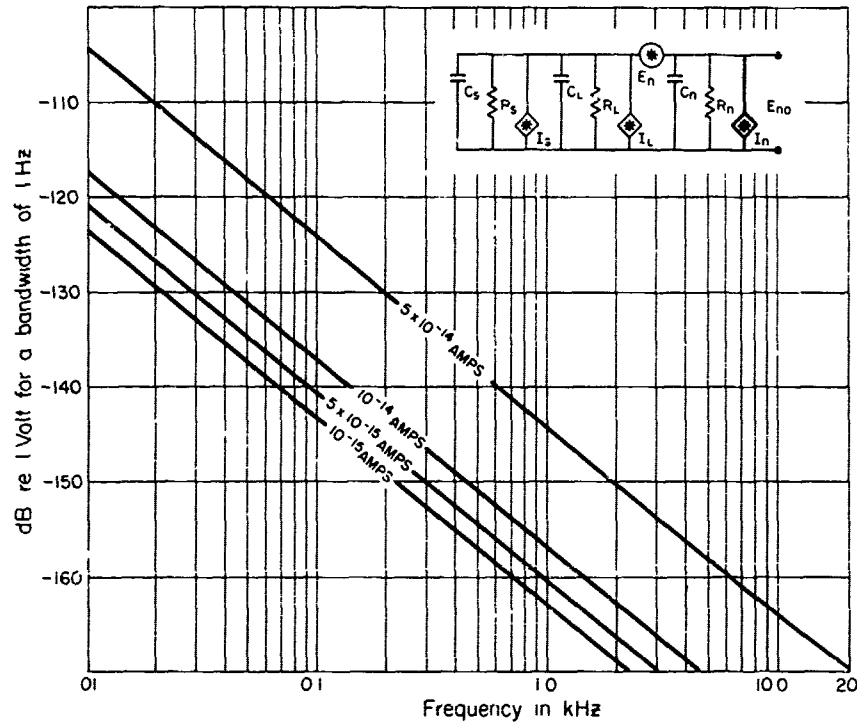


Fig. A10 - Equivalent noise output as a function of  $I_n$

## Appendix B

### JFETS FOR LOW-NOISE CIRCUIT APPLICATIONS

The JFET is a superior device for hydrophone preamplifier circuits when high input impedance and low self-noise are requirements. Input dc resistance for the JFET can be as high as  $10^{13}$  ohms. The input impedance is the impedance of a reverse-biased PN junction. However, in practice, the impedance is determined by the value of the gate shunt resistor ( $R_n$ ). When the generator impedance is highly resistive, as in piezoelectric sensors, the JFET is an excellent choice, particularly for infrasonic and audio-frequency applications.

In a low-noise JFET design the equivalent input noise voltage  $E_n$  is the significant parameter. On transistor data sheets  $E_n$  is usually given as  $e_n$  or  $V_n$  in  $nV/\sqrt{Hz}$ . Noise current is not normally given, because the FET is a voltage-actuated device with noise currents in the region of  $10^{-14}$  to  $10^{-15}$  A/ $\sqrt{Hz}$ . However,  $I_n$  can be important in low-frequency designs and it can be measured directly or calculated from the gate leakage current [B1, pp. 104-105].

Since  $E_n$  and  $I_n$  are frequency-dependent parameters, care should be exercised when comparing devices to note the frequency at which they are specified.

Devices are often specified as having a certain noise figure NF or a spot noise figure, instead of using  $E_n$ . Care should be taken again when comparing devices, because the NF depends on a specific generator impedance. A high value of generator resistance may make one device appear better than others.

The forward transconductance  $g_m$ , or  $g_{fs}$ , and the drain current at zero gate-to-source voltage  $I_{DSS}$  are also key parameters for low-noise designs. The transconductance determines the dynamic characteristics of the input circuit and the gain available from the FET. If a high-gain input stage is used, the signal-to-noise ratio can be large enough to negate the noise contributions of subsequent amplifier stages. The noise of the amplifier system will then be

$$E_{no} = E_n A_v, \quad (B1)$$

where  $A_v$  is the gain of the total amplifier system.

The  $g_m$  is also related to  $E_n$ , where  $E_n$  is inversely proportional to the square root of the transconductance [B2],

$$E_n \propto 1/g_m^{1/2}; \quad (B2)$$

therefore, as  $g_m$  increases,  $E_n$  decreases.

To minimize noise, it is necessary to operate the FET where  $g_m$  is at its highest value. The highest values of  $g_m$  are found at the high values of static drain current  $I_D$ , or when  $I_D$  is in the vicinity of  $I_{DSS}$ , where  $I_{DSS}$  is the drain current when the gate-to-source voltage  $V_{gs}$  is zero. Operation of the FET at a drain current near  $I_{DSS}$  provides superior noise characteristics. Practice has shown that an  $I_D$  as low as 0.1  $I_{DSS}$  does not cause a serious increase in  $E_n$  [B1, pp. 105-106].

A. C. TIMS

At higher frequencies other transistor parameters, such as input capacitance, become important; however  $E_n$ ,  $g_m$ , and  $I_{DSS}$  are the key parameters for low-noise infrasonic and audio-frequency designs.

#### REFERENCES

- [B1] C.D. Motchenbacher and F.C. Fitchen, *Low-Noise Electronic Design*, 1st edition, Wiley, New York, 1973.
- [B2] B. Watson, "Audio-Frequency Noise Characteristics of Junction FETs," Application Note AN74-4, Siliconix Inc., Santa Clara, Calif. Aug. 1974, p. 2.

## Appendix C LOW-NOISE HYDROPHONE PREAMPLIFIER

Figure C1 illustrates a typical preamplifier front end used in many low-noise hydrophone designs at the USRD. The common-source, common-collector pair has been used for voltage gains from 10 to 36 dB, with supply voltages from 12 to 48 volts, and with appropriate biasing. The circuit shown has a gain of 20 dB with a supply voltage of from +22 to +34 volts. The most favorable bias conditions occur when  $V_{cc}$  is +32 volts.

As stated in Appendix B, optimum low-noise characteristics exist when  $I_D$  of the FET is in the vicinity of  $I_{DSS}$ . For the preamplifier illustrated, the drain current over the given range of  $V_{cc}$  is  $0.4 I_{DSS}$  to  $0.9 I_{DSS}$ , depending on the specific  $I_{DSS}$  and pinchoff voltage characteristics of Q2. The nominal value of  $I_D$  is about  $0.6 I_{DSS}$  at optimum bias condition ( $V_{cc} = 32$  volts).

The input noise voltage and noise current for Fig. C1 are given in Table C1.

The choice of high-quality, low-noise bias components is essential for constant low-noise performance of a particular design. Bias resistors for the given circuit are of precision metal-film construction, type RN55, 1% tolerance, MIL-R-10509, except for the gate resistor. Resistor R4 is a high-megohm, thick-film, resistive-glass resistor of 5% tolerance. The input capacitor is a ceramic CK05BX type, MIL-C-11015. The emitter bypass capacitor is a solid-tantalum, established-reliability type, MIL-C-39003.

Table C1 – Input Noise Voltage  $E_n$  and Current  $I_n$  for Fig. C1

Frequency (Hz)	$E_n$ (V/ $\sqrt{\text{Hz}}$ )	$I_n$ (A/ $\sqrt{\text{Hz}}$ )
50	$5.6 \times 10^{-8}$	$2.5 \times 10^{-14}$
100	$6.7 \times 10^{-9}$	$2.5 \times 10^{-14}$
20 k	$5.6 \times 10^{-9}$	$2.5 \times 10^{-14}$

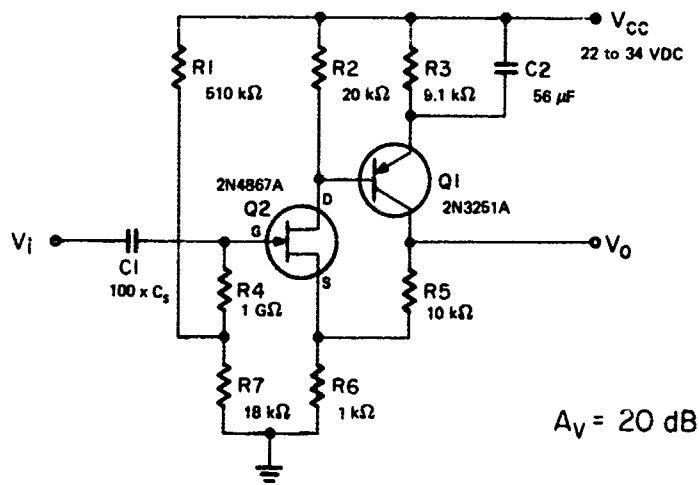


Fig. C1 – Typical USRD-type low-noise amplifier